The dynamic nature of sediment and organic constituents in TSS

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Abstract

The Chattooga River Watershed, located in NE Georgia, NW South Carolina, and SW North Carolina, contains some of the most scenic and valuable water resources in the region. The Chattooga River is designated as a wild and scenic river and serves as the headwaters for water supplied to numerous cities. The mix of public and private lands presents considerable challenges to addressing sources of stream degradation. The EPA has listed several streams in the Chattooga Watershed as being impaired by suspended sediment and has established Total Maximum Daily Loads (TMDLs). These TMDLs are based upon determining acceptable levels of suspended sediment; however, TSS was used as a surrogate for suspended sediment. We are using continuous monitoring of flow and sampling TSS, suspended sediment, and particulate organic matter on four tributaries of the Chattooga River to determine the nature of TSS loading in these streams. We have found that TSS concentrations do not necessarily reflect suspended sediment concentrations. The organic and mineral components of TSS vary between streams. While the benchmark, forested stream in our study did have lower levels of TSS, it did have relatively high TSS levels during storm events, similar to those of impacted streams. However, organic matter was a proportionately larger component of TSS in the forested streams whereas mineral sediment comprised the greatest fraction of TSS in streams more heavily impacted by land use change and roads. The streams listed as threatened or impaired had significantly higher levels of TSS than the benchmark stream. However, TSS and mineral sediment in one of the impaired streams were significantly lower than a stream listed as only being threatened. The relevance of a sediment TMDL based on suspended load is questionable because the sediment impacts to the stream biota and aquatic habitat are caused by bedload.

Introduction
The Chattooga River Watershed encompasses 450 square kilometers of the Blue Ridge Ecosystem in the southern Appalachian Mountains of NE Georgia, NW South Carolina, and SW North Carolina, Figure 1. The Chattooga Watershed contains some of the most scenic and valuable water resources in the region and the Chattooga River, federally designated as a Wild and Scenic River, is one of a few large free flowing rivers remaining in the entire United States. A large outdoor recreation economy has grown to depend upon the high quality land and water resources that provide for the numerous whitewater kayaking and rafting competitions, cold and warm water fisheries, large and small game hunting, hiking, mountain climbing, mountain biking competitions, swimming and camping opportunities.

The primary threat to the integrity of the aquatic resources of the Chattooga River watershed is sediment (Van Lear, et al, 1995). The main sources of this sediment are erosion from gravel and dirt roads, soil and streambank erosion in agricultural areas, and erosion resulting from development. Van Lear, et al (1995) reported that roads alone accounted for 80% of the observable sediment sources in the Chattooga Watershed.

The EPA has listed several streams in the Chattooga Watershed as being impaired by suspended sediment and has established Total Maximum Daily Loads (TMDLs) (EPA, 2001). This determination was based upon an effort by the EPA to quantify Georgia's qualitative water quality standards. Due to difficulties stemming from the interpretation of Georgia's water quality standards, the characterization of stream sedimentation, and judicially imposed time limitations for the establishment of TMDL's, the EPA has taken a phased approach in developing TMDLs for the Chattooga River Watershed. The EPA has published these TMDLs (2001). Acknowledging the afore mentioned issues, the EPA has stated that it will likely revise the TMDLs in 2004.

The Chattooga River Watershed is also the subject of an USDA Forest Service Large Scale Watershed Restoration project. As part of this project, the Forest Service has identified actions to improve the quality of water draining the national forest lands that account for 68% of the Chattooga watershed. One of the primary actions is the reduction of runoff, erosion, and sedimentation caused by forest roads through the implementation of road improvement projects, best management practices and, where necessary, closing roads. As part of this project, we have been intensively monitoring water quality and streamflow on four tributaries of the Chattooga River. One goal of this monitoring is to determine the quality of these streams with regard to sedimentation using long-term monitoring data and see how these results compare to those arrived at by the EPA through the TMDL process. We anticipate that our results will differ from those of the EPA because the EPA employed total suspended solids (TSS) data as a surrogate for mineral sediment in their determination of sediment impacts (Pruitt, et al, 2001). The second goal of this project is to determine the effectiveness of watershed restoration efforts. That research is still in progress.

Site Description
We selected four tributaries of the Chattooga River as study streams for this research; Addie Branch Creek, Pounding Mill Creek, Reed Mill Creek, and Roach Mill Creek. These streams are second order tributaries of the Chattooga River. Addie Branch Creek and Reed Mill Creek flow into the West Fork of the Chattooga River, a fifth order tributary of the Chattooga River. Roach Mill Creek and Pounding Mill Creek flow into Warwoman Creek, a fourth order tributary of the Chattooga River. The study streams' watersheds are located within the Chattahoochee National Forest of northeastern Georgia. This area is part of the Blue Ridge Ecoregion of the southern Appalachian Mountains (Pruitt, et al, 2001).

While the bedrock in the Blue Ridge belt is sedimentary and metamorphic, soils in the study area are derived exclusively from metamorphic crystalline bedrock. The loamy mountain soils derived from gneiss, mica-shist, quartz and granitic origin are highly erodible when exposed (Van Lear, et al, 1995). Elevation and terrain strongly influence climate, precipitation patterns, soil depth, soil moisture, solar insolation and the natural distribution of vegetation. High precipitation and mild temperatures place the regions mountain climate in the marine, humid temperature classification of Koppen's climate system (Swift, et al, 1988). Average annual rainfall at upper elevations is 230 cm per year while lower elevations receive approximately 180 cm of rainfall per year.

Ridgelines and upper elevation south facing slopes tend to be drier while slopes with northern aspects are moist and cool (Van Lear, et al, 1995). Swift, e t al (1988) reported that water yield and streamflow response of streams in this region; located at the Coweeta Hydrologic Laboratory, increase with elevation due to higher rainfall, shallower soils and steeper hydraulic gradients.

While forest harvesting took place in this region during the 1800's, the majority of the Chattoga Watershed was forested in the early 1900's (Van Lear, et al, 1995). An inventory of land use conducted in 1900 and 1901 indicated that the entire headwaters of the Chattooga, including all of the study stream watersheds, had standing merchantable timber of 1,000 to 5,000 board feet per acre (Ayres and Ashe, 1904). Forest harvesting increased greatly in the early 1910's and 1920's and spread into all of the study watersheds. Following harvesting, it is likely that mountain farming and grazing were practiced to some degree on the study watersheds. Local residents have indicated that mountain grazing was practiced in areas as remote as Addie Branch Creek during the 1930's. There is evidence of massive soil erosion and stream sedimentation in this region dating to this period (Leigh, 1996). Preliminary surveys of exposed floodplain sediments on the West Fork of the Chattoga River dating to the early 1900's indicate that flood plain building of up to 1 meter and subsequent channel scour have occurred (David Leigh, University of Georgia, Athens, unpublished results). The study stream watersheds were incorporated in the National Forests of the USDA, Forest Service beginning in the mid 1900's. Presently, with the exception of Reed Mill Creek, all of the land upstream of the sampling locations are owned and managed by the USDA, Forest Service. More specific descriptions the study streams are provided below.

Addie Branch Creek is the most remote of the study streams and, with a 5.6 km^2 watershed, the largest. The Addie Branch watershed is significantly higher in elevation than the other streams (Table 1) exposing it to greater amounts of precipitation.

Table 1: Summary of characteristics for study streams.

Stream	303 (d) Listing Status	Watershed Size (km^2)	Mean Elevation (m)	Mean Slope (%)	Aspect	TSS Sample size	OM Sample size
Addie Branch	Unlisted	5.6	925	19	ENE	255	66
Pounding Mill	Threatened	1.3	706	14	SSE	194	130
Reed Mill	Threatened	4.4	700	14	S	272	86
Roach Mill	Impaired	0.8	712	16	SSE	202	64

The Addie Branch watershed is also the steepest and most northerly facing watershed in this study, characteristics that foster wetter soils and generate more runoff than watersheds with gentler slopes, lower elevations and southern aspects, characteristics of the other watersheds in this study. Despite these important, underlying differences, we included Addie Branch in this study because the EPA established Addie Branch as a stream suitable to serve as a minimally impaired reference site (based upon stream water chemistry, aquatic habitat, and land use) for the establishment of TMDL's (Pruitt, et al, 2001). There is only one road crossing upstream of the sampling location on Addie Branch and this is more than 1 stream km away. Land use data from the National Land Cover Data project Multi-Resolution Land Characteristics (MRLC) initiative also indicate that the entire Addie Branch watershed is forested. Thirty-three percent of it is covered with deciduous forest, 25 percent by evergreen, and the remaining 42 percent is mixed deciduous and evergreen forest.

Pounding Mill Creek was included in this study because it has significant potential to be impacted by roads. A heavily used gravel road winds along Pounding Mill for nearly its entire length. There are numerous opportunities for runoff from this road to drain into Pounding Mill. We have observed that Pounding Mill appears to transport unusually large amounts of sand as bedload during low flows and in suspension during storm events. The Pounding Mill watershed is relatively small and it has relatively low, average gradient and average elevation, Table 1. While not listed as a 303 (d) list impaired stream, Pounding Mill was listed as a threatened stream. Land use on Pounding Mill upstream of the sampling location is comprised of 16 percent deciduous, 40 percent evergreen and 44 percent mixed forest.

Reed Mill Creek was included in this study because it has the potential to be impacted by roads and land use conversion. In addition, anecdotal observations of turbidity suggested that Reed Mill was heavily impacted by TSS, suspended sediments, and an unusually high amount of sand in its streambed. The Reed Mill watershed is the second largest, 4.4 km^2. The average elevation and slope are low, Table 1. As with Pounding Mill, Reed Mill is listed as a threatened stream. There are numerous gravel roads in the Reed Mill watershed. These roads cross Reed Mill and are frequently used by landowners to access private land in the watershed. While 97 percent of the land use upstream of the sampling location on Reed Mill is forested (17 percent deciduous, 37 percent evergreen, 43 percent mixed) the remaining three percent is agricultural or transitioning from forest to residential or agricultural, primarily in the valley bottom along Reed Mill.

Roach Mill Creek is the only stream in this study on the EPA's 303 (d) list for impaired streams. Roach Mill was assigned a phased TMDL for sediment because the EPA has determined that its biological community and habitat are impaired by excessive sedimentation (EPA, 2001, page 7). With a watershed of 0.8 km^2, Roach Mill has the smallest contributing area of all of the study streams. There are neither roads nor private land holdings upstream of the sampling location on Roach Mill. As with Addie Branch and Pounding Mill, land use is forested (26 percent deciduous, 24 percent evergreen, and 50 percent mixed forest).

Methods
During the spring of 2001, we installed an automated pumping sampler and stage recorder on each study stream to monitor stream stage, control sampling regime, and to collect water samples. Each sampler has a capacity to pump and store 24, 1000 ml water samples via a fixed-point inlet. We anchored each inlet to a 1 m rebar pin driven into the streambed. We also affixed a submerged pressure transducer to each rebar pin. These transducers recorded stream stage on 5 to 15 minute intervals, depending upon the storm flow hydrograph characteristics of each stream. Stage readings were automatically corrected for variations in atmospheric pressure. We established stream stage relative to a surveyed benchmark elevation at each stream. Stage readings taken by the pressure transducers were validated weekly by manually surveying stage to each benchmark. We developed stage discharge rating curves for each sampling site and programmed the pumping samplers to monitor streamflow using these rating curves. We measured discharge according to the USGS methods published by Buchanan and Somers (1969). We obtained discharge data a number of times during the highest spring storm flow events. Consequently, no samples were pumped during stream stages that significantly exceeded the highest points on our rating curves.

The samplers were programmed to draw 750ml samples under two discreet sampling regimes. This allowed us to capture stream water quality during baseline conditions and storm flow conditions. The baseline regime collected samples on a flow proportional basis. One 750 ml sample was pumped with the passage of a specified volume of water. Thus, sampling was more frequent during higher flows and less frequent during low flows. The storm flow regime captured water quality during storm events by sampling on a time proportional basis during the rising limbs of hydrographs. Time proportional sampling was initiated when stream stage rose above a specified level. The samplers then pumped one 750 ml sample every 15 minutes, up to a total of 16 samples and reverted to sampling on the flow proportional basis during the recession limbs.

We also checked our data for bias in sampling via the fixed-point inlets. Using a DH-48 depth-integrated grab sampler, we pulled depth-integrated grab samples weekly according to the methods of Thomas (1985). We then compared these to a simultaneously pumped sample. Due to the highly turbulent nature of these mountain streams, the water columns are very well mixed and we found that the water quality data obtained from the fixed-point inlet samples were unbiased when compared to depth-integrated samples.

While we have completed sampling for nearly an entire year, sample analyses considered here are limited to total suspended solids (TSS) for the period of March – September 2001. We gravimetrically analyzed all of the samples for TSS by filtration to 1.5 μm as given USGS (1978a). Gray, et al have found that this method of TSS analysis can underestimate TSS concentrations; however, because of the fine nature of TSS in the study streams,

underestimation of TSS by gravimetric means is likely not an issue (Pruitt, et al, 2001). We began organic matter component (OMC) and mineral sediment component (MSC) analyses on the samples in June 2001. The TSS samples were combusted in a muffler furnace to determine MSC, as ash free dry weight, and OMC as the difference between TSS and MSC in accordance with standard methods for water quality analyses as given by the USGS (1978b).

We analyzed these data for temporal trends by regressing them against Julian date. Statistical analyses were performed on the transformed data and fit with a mean function of the form $y = \beta_0 e^{\beta_1 x}$. We also constructed rating curves by regressing TSS, MSC and OMC against dimensionless discharge (discharge divided by flow weighted mean discharge) using the general mean function $y = \beta_0 x^{\beta_1}$. Our tests for significance in the regressions and difference in the coefficients were performed on the transformed data. We considered differences to be significant at the $\alpha = 0.1$ level using standard student T tests for paired samples with pooled variance.

Results
The TSS concentrations for Roach Mill, Reed Mill and Pounding Mill increased from spring, through summer, and into autumn (Figure 2, $r^2 = 0.14$, $r^2 = 0.11$, $r^2 = 0.18$, respectively and $p < 0.0001$ for each). Conversely, there was no trend in TSS concentration with time for the benchmark stream, Addie Branch ($r^2 = 0.00099$, $p = 0.91$). While the trends on Reed Mill and Roach Mill are similar, TSS concentrations in Reed Mill are consistently three to five times greater than those in Roach Mill ($p < 0.001$). TSS concentrations of Pounding Mill are greater than those in Roach Mill ($p = 0.058$).

In figure 3, we regressed the quotient of TSS and discharge against time ($p < 0.001$). The positive seasonal trend, as indicated by the slopes of the regression functions, of TSS concentration per unit discharge for all of the study streams was the same (lowest $p = 0.994$). The intercept of the TSS concentration per unit discharge for Pounding Mill is greatest followed by Reed Mill ($p = 0.0014$) and Roach Mill ($p < 0.001$). The TSS concentration per unit discharge for Addie Branch is the lowest by more than an order of magnitude ($p < 0.0001$).

TSS rating curves for each of the streams are plotted in Figure 4 ($p < 0.001$). TSS in Reed Mill exhibits the strongest dependence on discharge ($r^2 = 0.71$) while the relationship for Addie Branch ($r^2 = 0.31$) is the weakest. Increases in TSS with discharge are the highest on Roach Mill and Reed Mill ($p < 0.001$ for both) while Addie Branch has the most muted response ($p < 0.001$). The intercept of the Reed Mill rating curve is the highest, followed by Pounding Mill, Roach Mill, and Addie Branch ($p < 0.001$, inclusive).

Reed Mill was the only stream to exhibit a significant temporal trend in MSC and OMC, Figure 5. The ratio of MSC to OMC on Reed Mill increased at a rate of 5% per week ($r^2 = 0.15$, $p < 0.001$).

MSC rating curves for each of the streams are plotted in Figure 6 ($p < 0.001$, inclusive). As with TSS, the strongest dependence of MSC on discharge occurs on Reed Mill ($r^2 = 0.70$) while the relationship for Addie Branch is the weakest ($r^2 = 0.26$). MSC increases with TSS are also the highest on Roach Mill and Reed Mill ($p < 0.001$). Addie Branch has the most muted response ($p < 0.001$). As with TSS rating curve, the intercept on Reed Mill is the highest followed by Pounding Mill, Roach Mill Addie Branch ($P < 0.001$, inclusive).

Rating curves showing the regressions of OMC on discharge are graphed in Figure 7. The dependence of OMC on discharge for all of the study streams is less than that exhibited by MSC and TSS. Again, the relationship on Reed Mill is the strongest ($r^2 = 0.48$) while the relationship for Addie Branch ($r^2 = 0.22$) is the weakest. Unlike the rating curves for TSS and MSC, tests on the regression coefficients for each of the study streams indicate that the OMC component of TSS in Roach Mill and Addie Branch increases the most with discharge followed by Pounding Mill and Reed Mill ($p < 0.0001$, inclusive). The Reed Mill rating curve has the largest intercept, followed by Roach Mill, Pounding Mill and Addie Branch ($P < 0.001$, inclusive).

Discussion

TSS, MSC and OMC

To facilitate the interpretation of our results, we simplified the figures by ranking each stream's plotting position in Table 2. The rankings are based upon the significance of differences in the slopes and intercepts of each regression. A value of 1 indicates the stream experiencing the least impacts from seasonal and discharge driven trends in TSS and MSC. A value of 4 indicates the stream experiencing the greatest impacts from seasonal and discharge driven trends in TSS and MSC. When two regression lines intersected, the average of the two rankings was assigned to each stream. The last column is the mean of the previous ranks. Due to the influence of disproportionate storm flow sampling on TSS data, we excluded Figure 2 from this analysis. We omitted Figure 7 from this analysis because the influence of OMC on stream water quality is beyond the scope of this paper.

Table 2: Ranking of streams by degree of impairment caused by TSS and MSC.

Stream	303 (d) Listing Status	Figure 3: Seasonal unit TSS	Figure 4: TSS per unit discharge	Figure 5: MSC/OMC ratio	Figure 6: MSC per unit discharge	Average (stdev)
Addie Branch	Unlisted	1	1	1	1	1
Pounding Mill	Threatened	4	2.5	4	2.5	3.3
Reed Mill	Threatened	2.5	4	3	4	3.4
Roach Mill	Impaired	2.5	2.5	2	2.5	2.4

The impacts of seasonality and discharge on trends in TSS and MSC are significantly lower on the benchmark stream (Addie Branch) than they are on the threatened (Pounding Mill and Reed Mill) and impaired (Roach Mill) streams. Perhaps the most significant difference is that the TSS and MSC rating curves of Addie Branch are by far the weakest and have the lowest plotting positions. This indicates that TSS and MSC are far less dependent and less responsive to shifts in unit discharge on Addie Branch. Thus, TSS and MSC are introduced to Addie Branch from source areas that are dependent upon other driving variables. Wallace, et al (1991, 1997) has identified significant seasonal components to OMC cycling in mountain streams of the southern Appalachians. While the apparent seasonal decrease of the MSC : OMC ratio of Addie Branch over the duration of this study, suggesting an increase in OMC, is consistent with the findings of Wallace, et al (1991, 1997), the seasonal trend is not significant ($r^2 = 0.035$, $p = 0.17$). Other drivers of the seasonal dependence of TSS and MSC likely include time between storm events and chemical weathering. Addie Branch is a supply-limited stream. Its transport capacity far exceeds the availability of TSS and MSC.

Looking at the remaining streams, we see that Pounding Mill has the strongest seasonal trends in unit TSS and the highest MSC : OMC ratio (the intercept is significant at $p < 0.001$). This suggests that there is a source of TSS and MSC that has a strong seasonal component. We hypothesize that these patterns are signatures of mineral sediment from the gravel road that follows Pounding Mill for its entire length, providing a source of TSS that has a high MSC : OMC ratio. In addition, road derived TSS would increase and peak over the summer and into autumn as traffic increases with hunting and other recreation activities. The moderate strength of the TSS and MSC unit rating curves might also be indicative of the road as the primary sediment source. While rains generate TSS and MSC from the roadbeds, the rains have to be large enough to transport the TSS and MSC from the roads, through the drainage networks, and frequently overland before reaching the stream. While conducting fieldwork, it did appear that there was a threshold of rain required to increase stream turbidity. However, we do not have access to representative precipitation data for these remote sites.

Reed Mill has the strongest TSS and MSC unit rating curves and their plotting positions are higher than the other streams. This indicates that TSS and MSC are more dependent and responsive to shifts in unit discharge on Reed Mill than on Addie Branch, Pounding Mill, and Roach Mill. Thus, TSS and MSC in Reed Mill are mined from their source areas by the same processes than drive unit discharge. This suggests that there is a greater degree of internal sourcing of TSS and MSC within the channel of Reed Mill. Reed Mill is a transport-limited stream, the supply of TSS and MSC to Reed Mill are exceeding the capacity of Reed Mill to transport it. Erosion of

previously deposited sediments within the stream channel is frequently the source of sediment in transport-limited systems. Excessive sediment loading from erosion in upstream agricultural lands, disturbed residential areas, access roads and streambanks might be causing the deposition of in-channel sediments that are transported downstream by subsequent storm events.

The last stream, Roach Mill, is perhaps the most interesting. While it exhibits a modest seasonal trend in TSS similar to Reed Mill, the discharge dependent trends in TSS and MSC are similar to those of Pounding Mill. The impacts of TSS and MSC on water quality in Roach Mill are greater than those of the benchmark stream, Addie Branch, and less than those of the threatened streams, Pounding Mill and Reed Mill. While the MSC to OMC relationship for Roach Mill appears to be similar to that of Addie Branch, the trend is not significant.

While there do appear to be seasonal trends in OMC, most of them were not significant. Long term studies by Wallace, et al (1997) on the seasonal dynamics of TSS, MSC and OMC in other regions of the southern Appalachians have shown that OMC has a strong seasonal trend, beginning with a minimum in autumn, rising through winter, spring and summer and then declining again into the autumn. This trend has been attributed to interactions between the incorporation of coarse organic matter into streams by summer stormflows, temperature, the occurrences of the annual invertebrate population maxima and invertebrate feeding habits and annual leaf litter standing crop maxima (Wallace, et al, 1991). While such processes are likely at work in our study streams, our sampling methods may not have been suitable to quantify the complicated dynamics of aquatic OMC cycling.

Conclusion
It is evident that the impacts of seasonally and discharge driven trends in TSS and MSC on water quality are minimal on the benchmark stream (Addie Branch), greatest on the 303 (d) list threatened streams (Reed Mill and Pounding Mill), and intermediate on the 303 (d) list impaired stream, Roach Mill. Does this indicate that the 303 (d) listing status of Roach Mill as impaired is incorrect? Possibly, but the 303 (d) status of these streams were established based upon a combination of sediment and biological factors. The invertebrates sampled during the TMDL establishment process are holistic indicators of water quality. As such, the health of these communities is also dependent upon biological indicators not addressed in this study. The invertebrates depend upon stream substrate for existence. The dynamics of the entrainment and transport of suspended particulate matter such as TSS, MSC and OMC are often not reflective of the dynamics and entrainment of sediments transported as bedload. By far the greatest impact of sedimentation on our study streams was that exerted by coarser sands moving as bedload. In the most impacted reaches, we observed sand deposits that exceeded 30 cm in depth and sand accumulated in riffles during periods of low flow. Excessive sedimentation of stream substrates such as this greatly impacts aquatic biota and substrate habitat (Henley, et al, 2000). We believe that the TMDLs established using TSS data fail to address this issue. The TMDLs should be based upon sediments moving as bed material load. These are the sediments most likely to come from the erosion of forest roads and streambanks, sources previously identified as the primary contributors of sediment to the Chattooga River (Van Lear, et al, 1995).

Acknowledgements

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Figure 1: Project Location Map

Title:

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ArcView Version 3.0
Preview:
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PostScript printer, but not to
other types of printers.

Figure 2: Total suspended solids data by Julian Date for study streams.

$y = 1.94e^{0.0078x}$ $y = 5.91e^{0.0054x}$ $y = 1.63e^{0.0027x}$ $y = 1.40e^{0.014x}$
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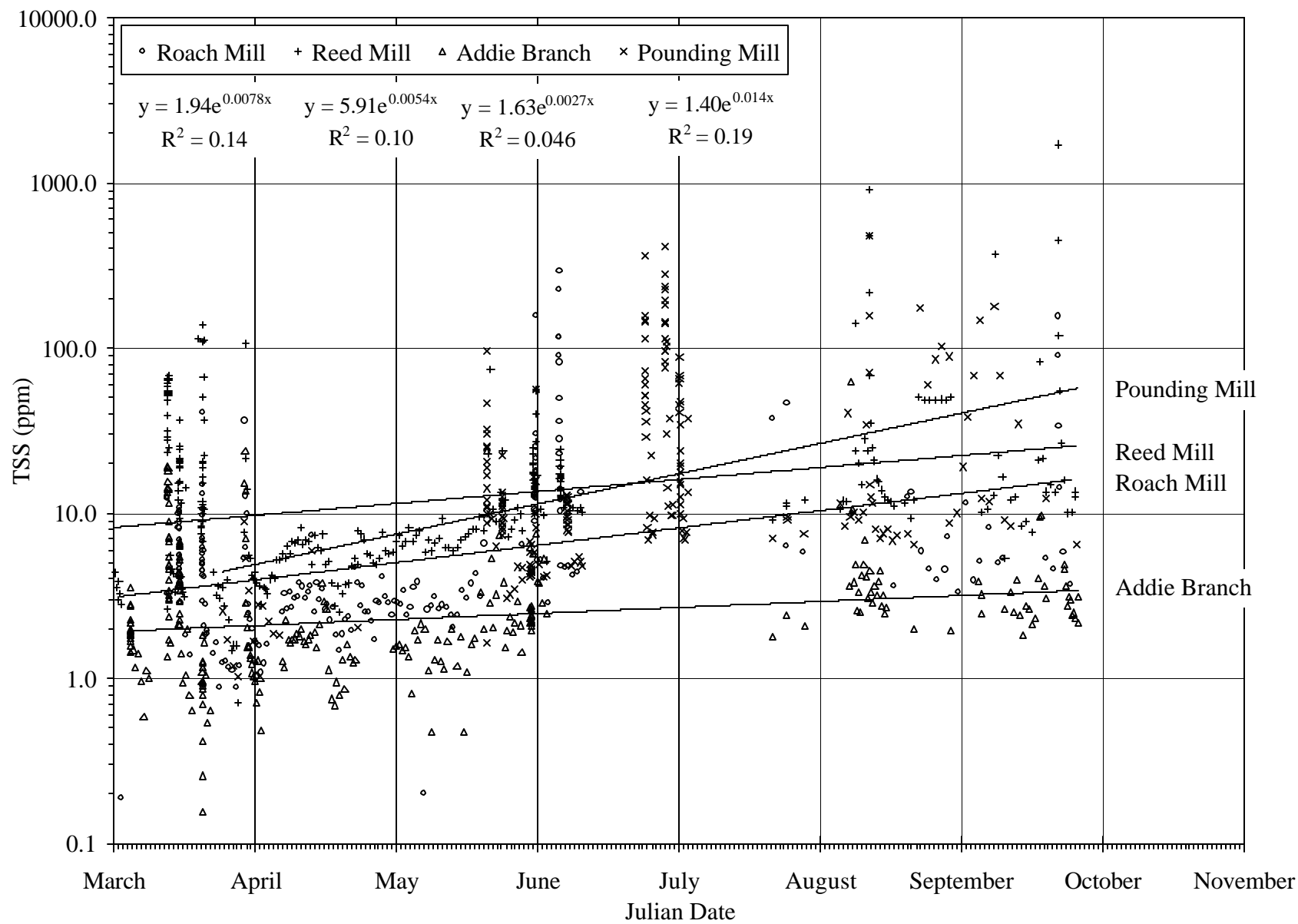
Figure 3: Regression of total suspended solids per unit discharge against Julian date.
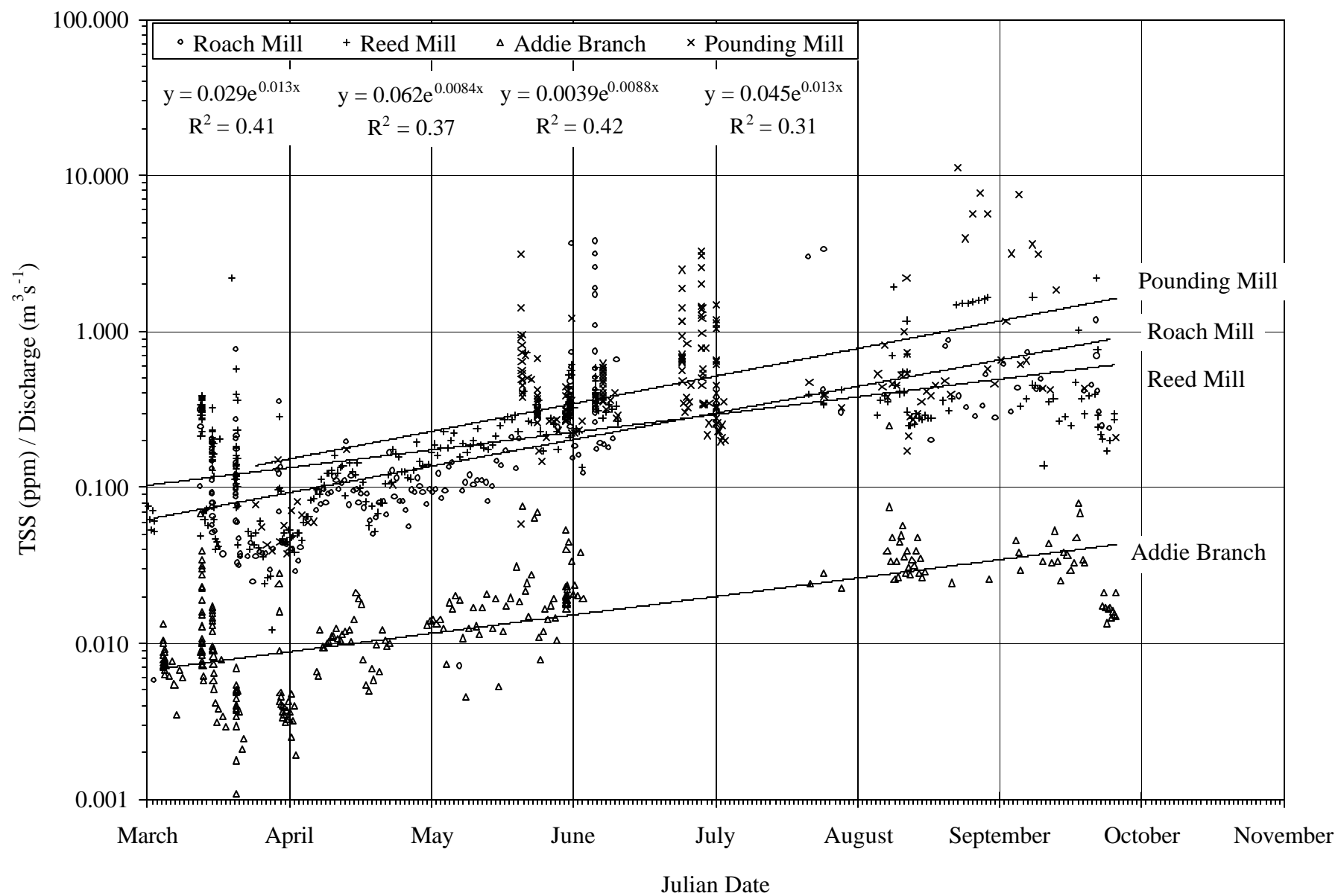
Figure 4: Rating curves of TSS regressed on dimensionless discharge. Dimensionless discharge is calculated as discharge at sampling divided by the average instantaneous discharge.
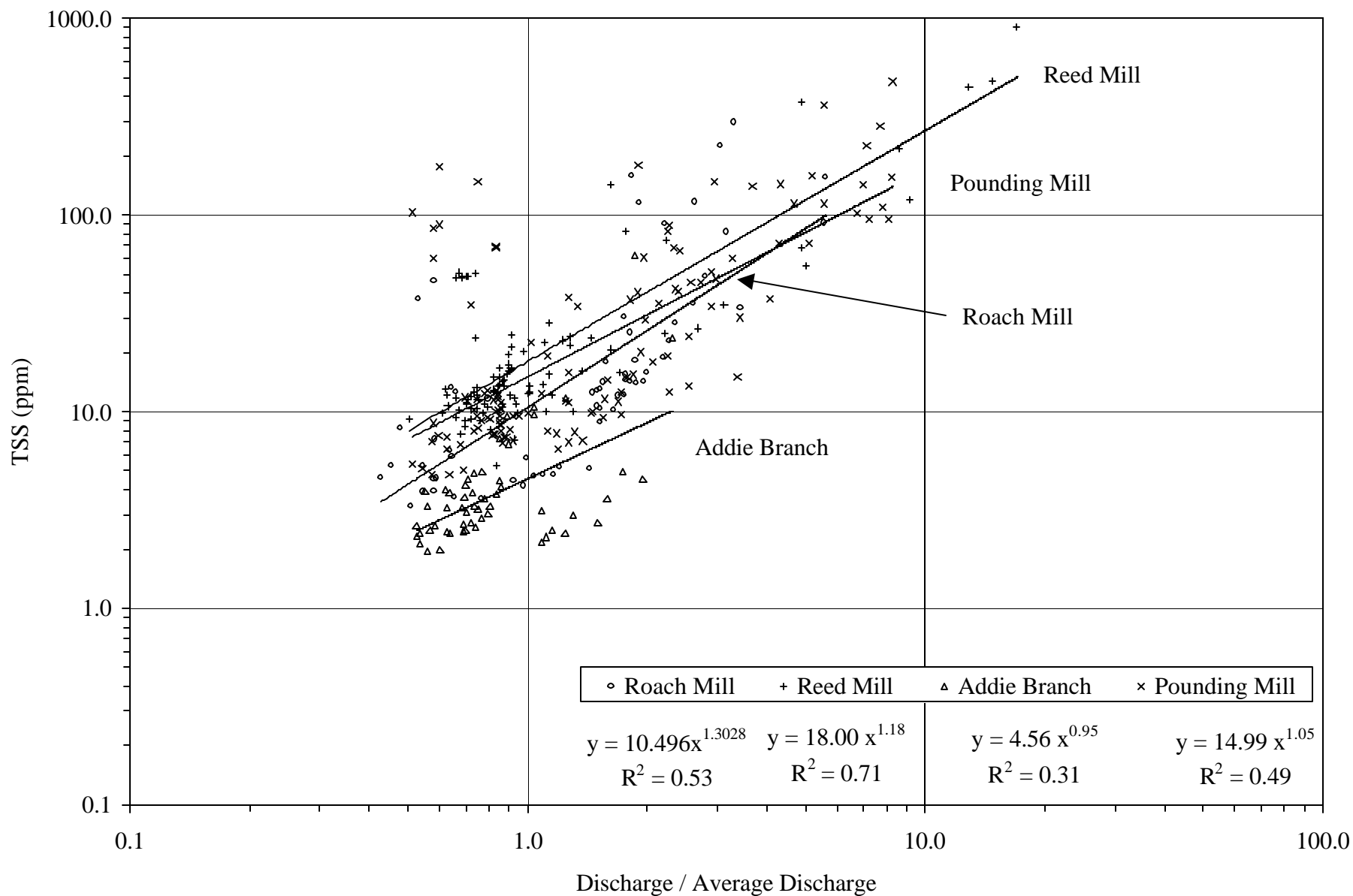
Figure 5: Temporal trends in the ratio of mineral to organic matter in TSS for the study streams.
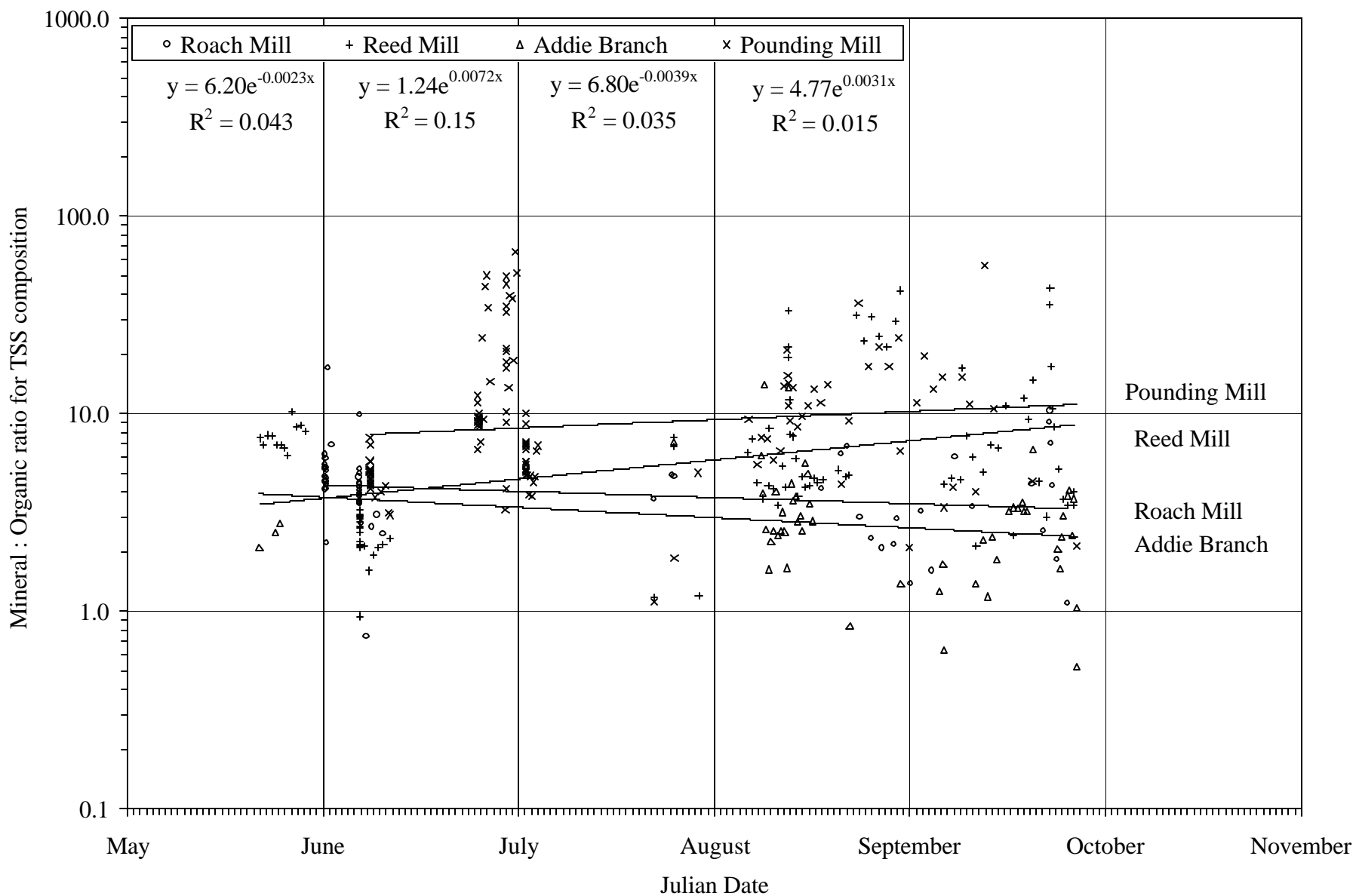
Figure 6: Rating curves of mineral sediment regressed on dimensionless discharge. Dimensionless discharge is calculated as discharge at sampling divided by the average instantaneous discharge Dimensionless rating curve for mineral component of TSS.
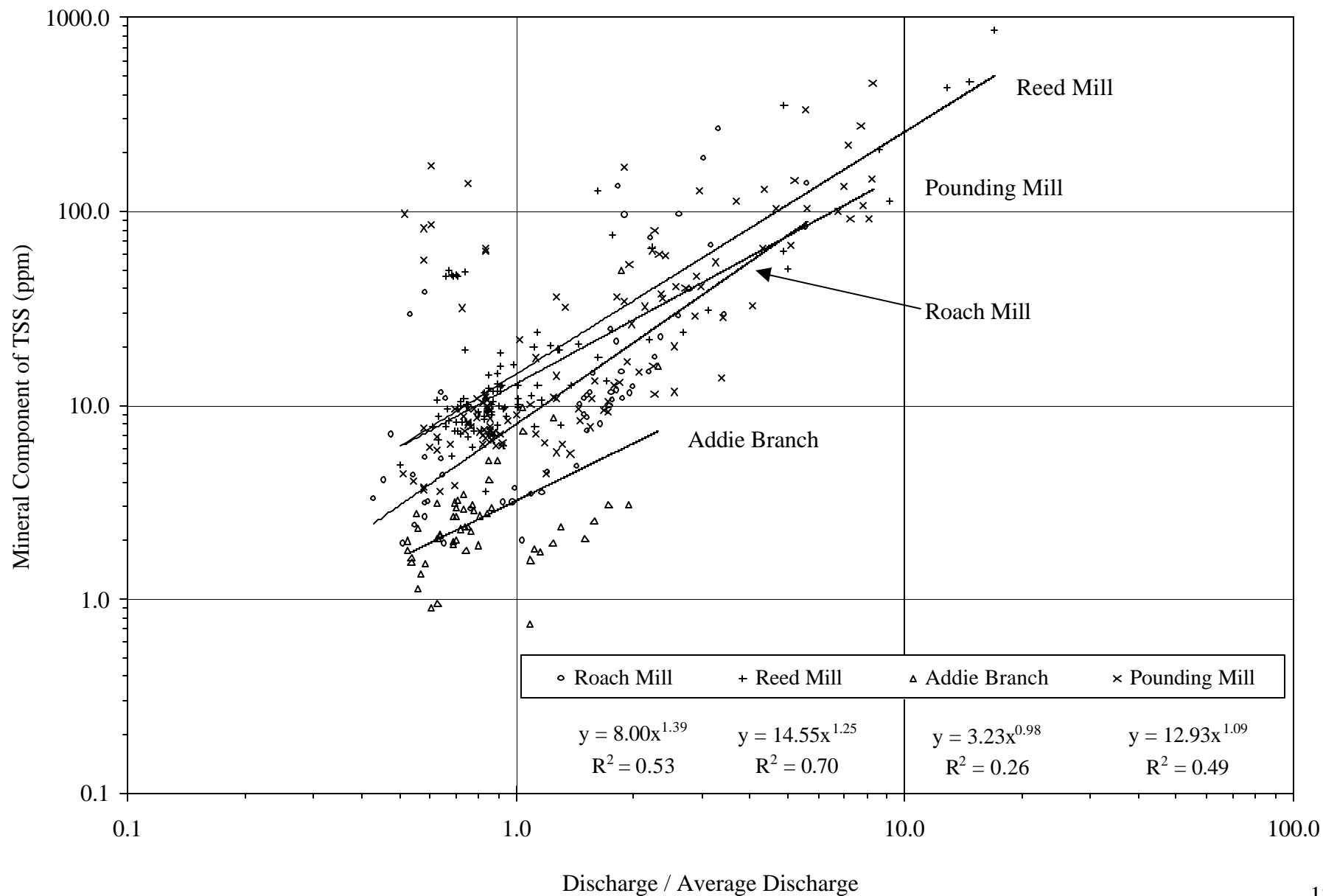
Figure 7: Rating curves of organic matter regressed on dimensionless discharge. Dimensionless discharge is calculated as discharge at sampling divided by the average instantaneous discharge Dimensionless rating curve for organic component of TSS.